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VALIDATION OF CATHARE 3D MODULE ON LSTF CORE

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ABSTRACT

CATHARE is the French thermal-hydraulic code for safety analysis of nuclear reactors. Its three-dimensional (3-D) module is mainly used to model the reactor vessel where 3D effects occur during a loss-of-coolant accident (LOCA).

The OECD/NEA ROSA-2 Project Test 3 (SB-HL-18 in JAEA) was conducted with the Large Scale Test Facility (LSTF). This test simulated a PWR 1.5% hot-leg Small Break Lost Of Coolant Accident (SB-LOCA). During this test, the core uncovers twice.

A 3D modeling of the LSTF core has been made with CATHARE code, and the experimental evolutions at the core boundary during the core uncover phases of Test 3 have been reproduced in the calculations. This paper will compare the experimental evolutions of the cladding temperature with the calculation results during the core uncover phases.

The results show that the 3D module of the CATHARE code is validated to deal with Intermediate Break LOCA (IB-LOCA) core uncover accidental situations which is essential in safety studies. No shortcoming is associated with the use of closure relations (interfacial friction in rod bundle geometry and wall to vapor heat flux) taken from a 1-D model. This article will also show that in a PWR accidental situation with a core uncover phase, the use of a 3-D modeling of the core is necessary because of 3D effects occurring in the core.

KEYWORD

LOCA, CATHARE, LSTF/ROSA, 3D MODULE, VALIDATION

1. INTRODUCTION

CATHARE [1] is the French thermal-hydraulic system code for safety analysis of nuclear reactors. It has a 3D modules in porous medium approach which were initially devoted to the prediction of very large scale 3D effects during Large Break LOCA (LB-LOCA). CATHARE was validated on the data of the 2D-3D experimental program performed in UPTF, SCTF or LOFT facilities (see [2] [3] [4]). Since 3D module of CATHARE code is now used for the safety studies of Intermediate Break LOCA (IB-LOCA) [6] and will be used for real-time simulators [7], its 3D module has to be validated against a high pressure test, representative of the thermal-hydraulic conditions which occurs during SB/IB-LOCA core uncover phases.

The OECD/NEA ROSA-2 Project Test 3 (SB-HL-18 in JAEA) was conducted with LSTF. During this test, the core uncovers twice. The core component of LSTF has been modeled with the CATHARE 3D Module and the core uncover transients have been computed.

This article will first present the 3D Module of CATHARE with its basic set of equation and its main closure laws. Then, the core component of LSTF, the Test 3 of ROSA-2 program and their CATHARE modelling are described. In part 4, experimental evolutions are compared to CATHARE calculation’s results.

2. THE 3D MODULE OF CATHARE

The 3-D Module of CATHARE is based on a “porous” version of the two-fluid 6-equation model [8]. To obtain this model, the local instantaneous two-phase balance equations are double-averaged: first time-averaged to filter the pseudo-aleatory variations of the flow variables due to turbulence and two-phase intermittence, and then space-averaged to account for the interactions of the flow with the internal solid structures. Thus, the complex and relatively small structures such as rod bundles, grids, guide tubes, are managed *via* a porous medium approach. The mass, momentum (one in each direction) and energy balance equations (Eq. 1 to 3) are written for each phase k (liquid or gas):

$$\phi \frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\phi \alpha_k \rho_k \mathbf{V}_k) = \phi (-1)^k \Gamma \quad (1)$$

$$\alpha_k \rho_k \left(\frac{\partial \mathbf{V}_k}{\partial t} + \mathbf{V}_k \cdot \nabla \mathbf{V}_k \right) + \alpha_k \nabla P = p_i \nabla \alpha_k + (-1)^k \boldsymbol{\tau}_i + \boldsymbol{\tau}_{wk} + \alpha_k \rho_k \mathbf{g} \quad (2)$$

$$\phi \frac{\partial \alpha_k \rho_k e_k}{\partial t} + \nabla \cdot (\phi \alpha_k \rho_k e_k \mathbf{V}_k) = \phi (-1)^k \Gamma H_k + \phi q_{ke} + S_c q_{wk} - P \left[\phi \frac{\partial \alpha_k}{\partial t} + \nabla \cdot (\phi \alpha_k \mathbf{V}_k) \right] \quad (3)$$

In these equation, the main variables are the enthalpy H_k ; the volume fraction α_k (with $\alpha_L + \alpha_G = 1$); the pressure P and the velocity \mathbf{V}_k . The density ρ_k is determined with an equation of state: $\rho_k = f(P, H_k)$ and the internal energy e_k is calculated with the enthalpy ($e_k = f(P, H_k)$). The porosity ϕ and the heating surface S_c are set by the user for each mesh. The closure terms (in red in the equations) are the interfacial pressure p_i ; the interfacial friction $\boldsymbol{\tau}_i$; the wall friction $\boldsymbol{\tau}_{wk}$ with the phase k ; the interfacial heat transfers q_{ke} of the phase k ; the wall heat transfers q_{wk} with the phase k and Γ is the interfacial mass transfer calculated with:

$$\Gamma = \frac{S_c * q_{pi} - q_{ge} - q_{le}}{H_G - H_L} \quad (4)$$

With q_{wi} the wall-to-interface heat flux.

A general overview of CATHARE’s closure law can be found in [9]. In this paper, only the main closure laws involving in the simulation of the core uncover phase are described. The interfacial friction is the main parameter to determine the swell level in the simulations and the wall to gas heat transfer in the dry zone determine the gas and the cladding temperatures. These closure laws have been established for the 1D Module and extended to the 3D Module.

The general form of the interfacial friction $\boldsymbol{\tau}_i$ in CATHARE is the following:

$$\boldsymbol{\tau}_i = f_i \cdot \Delta V_2 \cdot k(\alpha) \quad (5)$$

Where f_i is a friction coefficient, ΔV_2 is the square of a velocity difference and $k(\alpha)$ is a numerical function that allows to strongly couple the phases when one of them tends to disappear. The square of the velocity difference is given by:

$$\Delta V_2 = \begin{cases} (\Delta V^2 + V_0^2) \text{sign}(\Delta V) & \text{if } |\Delta V| > V_0 \\ 2V_0 \cdot \Delta V & \text{if } |\Delta V| < V_0 \end{cases} \quad (6)$$

With $\begin{cases} V_0 = 0.1 \text{ m} \cdot \text{s}^{-1} \\ \Delta V = V_G - C_k V_L \\ C_k = 1 + 1.6 [\alpha_G \cdot \alpha_L]^{1.5} \end{cases}$

The numerical function $k(\alpha)$ is given by:

$$k(\alpha) = 1 + \frac{10^{-7}}{\alpha_G^3} + \frac{3 \cdot 10^{-15} P}{\alpha_L^3} \quad (7)$$

There are many correlation in CATHARE for the friction coefficient, depending of the flow regime and the geometry. In the wetted zone of the LSTF core during the simulated transients; the interfacial friction is given by the correlation for Bubbly-Slug-Churn flow in rod-bundle geometry:

$$f_i = \left\{ \frac{K_L \cdot \rho_L + K_G \cdot \rho_G}{\mathcal{L}} + \frac{\rho_G \cdot C f_v}{D_H} \right\} \cdot \alpha_G \cdot \alpha_L^{PK} \quad (8)$$

With $PK = 3.35$

This f_i expression is equivalent to the following drift velocity model:

$$V_{gj} = \left[\frac{\mathbf{g} \cdot \Delta\rho \cdot \mathcal{L}}{\frac{\rho_G \cdot C f_v \cdot \mathcal{L}}{D_H} + K_L \cdot \rho_L + K_G \cdot \rho_G} \right]^{1/2} \quad (9)$$

All terms have physical justification:

$\frac{\rho_G \cdot C f_v \cdot \mathcal{L}}{D_H} V^2$	The vapor friction over liquid films along the rods
$K_G \cdot \rho_G V^2$	The vapor singular pressure drop due to irregularities in bubble shape
$K_L \cdot \rho_L V^2$	The liquid singular pressure drop due to recirculation in the wake
$\mathbf{g} \cdot \Delta\rho \cdot \mathcal{L}$	The liquid/vapor gravity force difference

The bubble size is related to the Laplace scale $\mathcal{L} = \sqrt{\frac{\sigma}{\mathbf{g}(\rho_L - \rho_G)}}$

\mathbf{g} is the gravity constant and σ is the superficial tension, coefficients have been fitted using experimental data: $K_L = 1.063 \cdot 10^{-2}$; $K_G = 0.752$; $C f_v = 37.045$

In the dry zone, there is no liquid in contact with the walls and the wall to vapor heat transfer mechanism (q_{wg}) in CATHARE is equal to (there is a few contribution of radiation heat transfer, not describe here):

$$q_{wg} = \max(h_{lam}^{nc}; h_{turb}^{nc}; h_{lam}^{fc}; h_{turb}^{fc}) \cdot (T_W - T_G) \quad (10)$$

T_W is the wall temperature and T_G the gas temperature, the different heat transfer coefficients correspond to different heat transfer regimes which are:

- The laminar natural convection regime with $h_{lam}^{nc} = \frac{\lambda_G}{D_{HG}} \cdot 0.401 (Gr_G \cdot Pr_G)^{1/4}$
- The turbulent natural convection regime with $h_{turb}^{nc} = \frac{\lambda_G}{D_{HG}} \cdot 0.12 (Gr_G \cdot Pr_G)^{1/3}$
- The laminar forced convection regime with $h_{lam}^{fc} = 3.66 \frac{\lambda_G}{D_{HG}}$
- The turbulent forced convection regime with $h_{turb}^{fc} = \frac{\lambda_G}{D_{HG}} \cdot 0.023 Re_G^{0.8} Pr_G^{0.4}$

These coefficients are derived from standard heat transfer coefficients (McAdams and Dittus-Boelter), with constants fitted on experimental data in rod bundle geometry. The Prandtl number Pr_G , is taken equal to 1; the Reynolds number Re_G and the Grashof number Gr_G are computed with:

$$Re_G = \frac{\rho_G (|V_G| + 0.01) D_{HG}}{\mu_G} \quad (11)$$

$$Gr_G = \frac{\mathbf{g} \rho_G^2 D_{HG}^3 |T_W - T_G|}{\mu_G^2 T_G}$$

With $D_{HG} = D_H (1 - \sqrt{1 - \alpha_G})$; D_H is the hydraulic diameter set by the user. λ_G and μ_G are the heat conductivity and the viscosity of gas.

3. CATHARE 3D MODELLING OF THE LSTF CORE

The OECD/NEA ROSA-2 Project [10] was performed to resolve key safety issues of PWR Thermal-hydraulics by means of LSTF experiments at the Japan Atomic Energy Agency (JAEA). The core component of the experimental facility and the Test 3 are first described, then, the CATHARE modelling is described.

3.1. ROSA-2 Test 3 Description

LSTF is a full-pressure and full-height integral test facility using a full-height core (3.66m of heating length) composed of 1008 simulated fuel rods with 10 MW electrical power. The rods are regrouped in 24 assemblies: 45 heating rods and 4 non-heating rods for 16 square 7*7 bundles and 8 semi-crescent shaped bundles. The radial power profile is devised in 3 zones (high, mean and low) with radial peaking factor of 1.51 for the high power assemblies, 1.0 for the mean power assemblies and 0.66 for the low power assemblies. Fig. 1 presents the radial power distribution. All electrical fuel rod have the same cosine-shaped axial power profile. Test 3 is a Hot-Leg SB-LOCA transient during which two core uncover phases took place:

- The High Pressure phase which is about 300s long at around 7MPa, during this transient, the maximum measured cladding temperature was 780K [10].
- The Mean Pressure phase which is about 500s long at around 4MPa, during this transient, the maximum measured cladding temperature was 822K [10].

For both transients, liquid level drop down from the top of the core to half height by boil-of (due to the electrical power) and a cladding temperature excursion took place in the dry zone. Experimental data package [11] provide us the evolution of:

- Some heating rods cladding temperatures (localized at the center of the assemblies) for 9 elevations of the core,
- Some fluid temperatures (localized at the corner of the assemblies on non-heating rods) for 9 elevations of the core,
- Fluid temperature at the core inlet, which is at the saturation temperature (or just few °C lower) all during both transients,
- The system's pressure (measured in the upper plenum)
- The electric power level injected in the core
- The collapsed level (obtained with ΔP measurement)

The swell level evolution can be obtained thanks to the heating rods thermocouple: the temperature starts rising above the saturation temperature when the swell level is at the thermocouple elevation. Moreover, the thermocouple evolution show that swell level is radially uniform all along both transients. We will focus on only a quarter of the core, thanks to the symmetrical radial power distribution, we manage to regroup all temperatures measurements in the same quarter (more precisely the core geometry and power distribution is symmetrical per 1/8), if the core behavior is symmetrical. Thank to that, we will only focus on few well instrumented assemblies for calculation/experimental comparison. As presented below, symmetrical behavior of the core during the core uncover transients has been checked.

Fig. 1 presents the thermocouples localization (TW for the wall cladding temperature and TE for the fluid temperature) in a quarter of LSTF core (regrouped thank to symmetrical consideration) at two elevations in the dry zone for the high power assembly. At elevation 7, TW287 and TW341 thermocouples and TE283 and TE277 thermocouples come from different quarters of LSTF core and can be localized at the on the same radial position thank to symmetrical consideration (TE293 and TE226 thermocouples at elevation 8 too).

High Power Assembly

Mean Power Assembly

Low Power Assembly

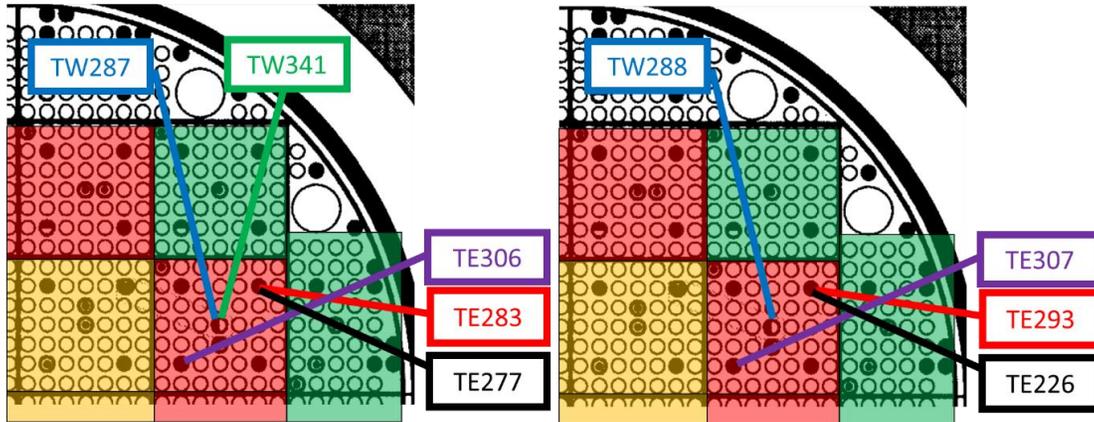


Fig. 1: Thermocouple localization in the high power assembly for elevation 7 (left) and 8 (right) of the LSTF core – High Power Assemblies are in red, Mean Power Assemblies in yellow and Low Power Assemblies in green

Fig. 2 and Fig. 3 show the experimental temperature evolutions for elevation 7 and 8 for both transients.

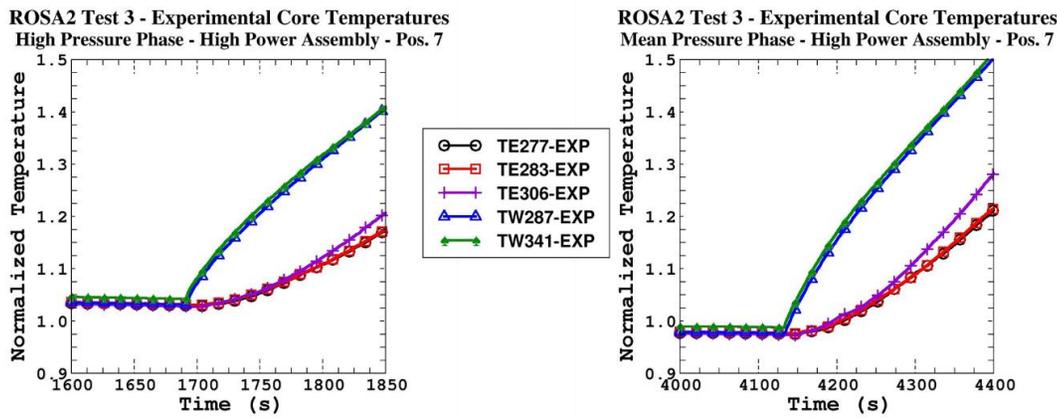


Fig. 2: Experimental temperature evolutions at elevation 7 for the High (left) and Mean (right) Pressure transients

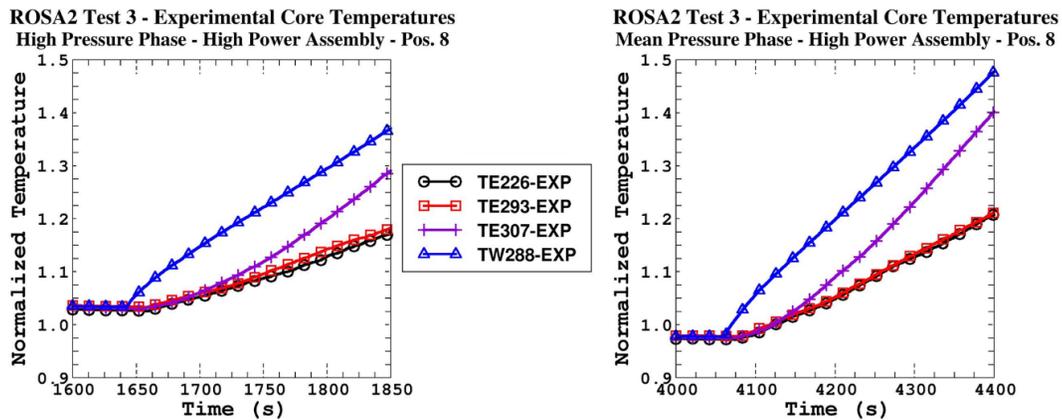


Fig. 3: Experimental temperature evolutions at elevation 8 for the High (left) and Mean (right) Pressure transients

First, one can see that TE277 and TE283 evolutions on Fig. 2; TW287 and TW341 evolutions on Fig. 2 and TE226 and TE293 evolutions on Fig. 3 are identical which confirm the symmetrical behavior of the core during the core uncover transient.

Moreover, all fluid temperature thermocouples are localized at a corner of the high power assembly, one row away from the assembly boundary. If there is no cross-flow between assemblies, their evolutions should be the same. But, TE306 at elevation 7 and TE307 at elevation 8 are localized next to one high power assembly and one mean power assembly while the other fluid temperature thermocouples are localized next to two low power assemblies. “Chimney” effect is expected in these conditions, as explain in [12] and [13], and brings some ‘cold’ vapor from the low power assemblies to the high power assembly. This phenomena is observed for both transients and both elevations on the experimental evolutions with a vapor temperature lower next to the low power assemblies. The vapor temperature differences reach an important value (more than 50°C).

This constitute a direct experimental evidence of the “Chimney” effect. The “Chimney” effect will be shown in the calculation.

Other symmetrical verifications have been made, all give a symmetrical behavior of the core except for the last elevation of the core (elevation 9). The elevation 9 thermocouples are just below the core upper plate, this plate is not symmetrical which can explain the non-symmetrical behavior. So, the elevation 9 thermocouples will not be used in the CATHARE/experiment comparisons.

3.2. CATHARE 3D Modelling

As we only consider a quarter of the LSTF core for the experimental evolutions, only a quarter model of the core has been made. The chosen meshing is a radial meshing of one mesh per assembly (3*3 radial meshes) and 48 axial meshes (45 for the heating length and 3 for the top part of the core, bellow the core upper plate). The 252 (1008/4) heating rods are modelled with their axial power profile taken from experimental data and all non-heating structures (dunny rods, tie rods, core barrel ...) are modelled too. The flow geometry has been taken equal to ‘Rodbundle’, allowing using specific correlations for rod bundle geometry (including the interfacial friction coefficient presented in part 2). The porosity and the hydraulic diameter have been calculated using the geometric data of the experimental facility. Singular pressure drops have been added in the model:

- In the axial direction, singular pressure drops have been added to take into account the mixing grids, the coefficients have been fitted on experimental nominal values (nominal flowrate and nominal core ΔP)
- In the radial directions, singular pressure drops have been added to take into account the influence of the rods on the transversal flow. The taken coefficient is given by Idel’cik.

To calculate the core uncover transients, the following conditions are imposed:

- The power injected in the heating rod is following the experimental power evolution,
- The outlet boundary condition is a pressure imposed conditions and its value follow the experimental pressure,
- The inlet boundary condition imposes monophasic saturated liquid flow. During the transient, the calculated collapsed level is compared to the experimental one and the inlet flowrate is regulated to follow the experimental evolution of the collapsed level.

A systemic verification of the core ΔP is made, in order to verify if the inlet flowrate regulation is correct.

Thank to that, a well instrumented Separated Effect Test (SET) with two transients is obtain. These tests can now be used to validate the 3D Module of CATHARE on experimental condition representative of IB-LOCA core uncover situations.

These tests are similar to PERICLES-2D Boil-Up tests for LB-LOCA [14] (PERICLES-2D is 3 full height PWR half assemblies with non-homogeneous radial power profile and the Boil-Up tests are core uncover tests in LB-LOCA pressure conditions – 3 bars).

4. COMPARISON BETWEEN CATHARE AND THE EXPERIMENT

In this section, a comparison between the experimental results and the calculation results obtained with the CATHARE code is presented for both transients. First, we will focus on the swell level evolution and next, we will focus on the behavior of the dry zone.

4.1. Swell Level Evolution

The comparison between CATHARE calculations and the experience on the swell level evolution are shown on Fig. 4. This comparison shows that the interfacial friction correlation of CATHARE well predict the swell level evolution. The CATHARE code overestimate just a little the swell level with a difference between CATHARE evolutions and experimental evolutions less than 16cm, which is the order of magnitude of the experimental uncertainty on the collapse level. But this little gap leads to a delay (of about 20s) on the dry out time of the thermocouple (see Fig. 5). In order to have better comparisons between CATHARE and the experimental cladding temperature, the interfacial friction coefficient has been a little reduced to have a better predicted swell level evolution and to have the same time of dry out for the thermocouples. The next presented results will use this optimized interfacial friction.

Moreover, the radial transfers under the swell level are also well predicted, which lead to a radially homogeneous swell level. Indeed, cladding temperatures in the different assemblies start rising at the same time in both CATHARE and the experience (see Fig. 6 and Fig. 9). The radial mixing lead to a homogeneous vapor mass flux at the swell level as predicted by CATHARE although if the vapor production is different between assemblies under the swell level (see Fig. 8).

To conclude on the interfacial friction, we can say that the interfacial friction correlation of CATHARE is validated to deal with core uncover phase in IB-LOCA conditions with a difference between the experience and the calculation of the same order of magnitude of the experimental uncertainty.

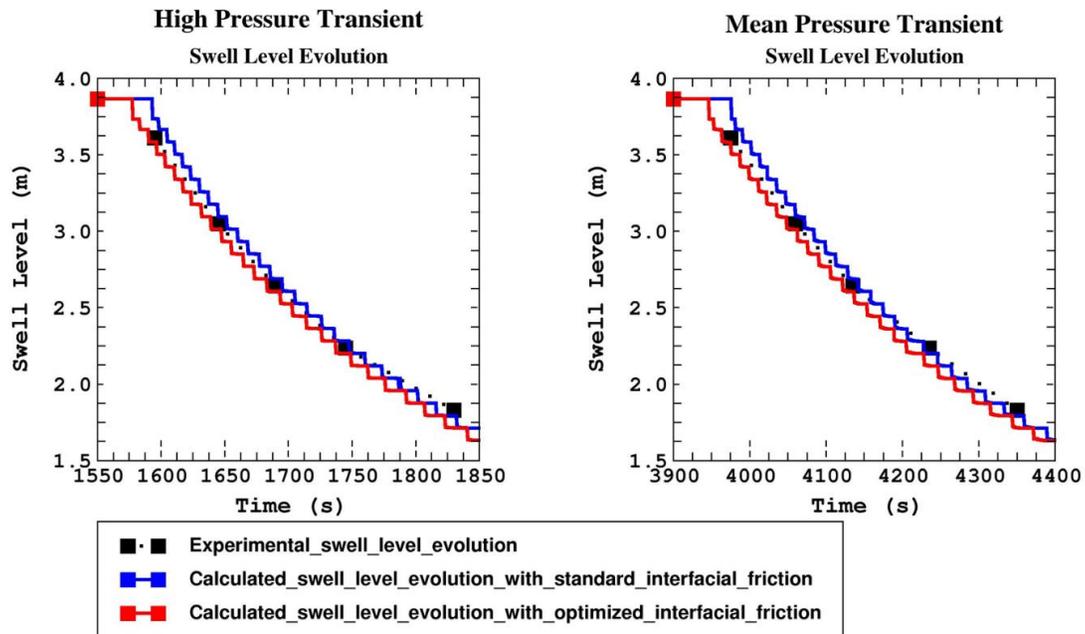


Fig. 4: Swell level evolution for the High (left) and Mean (right) Pressure transients

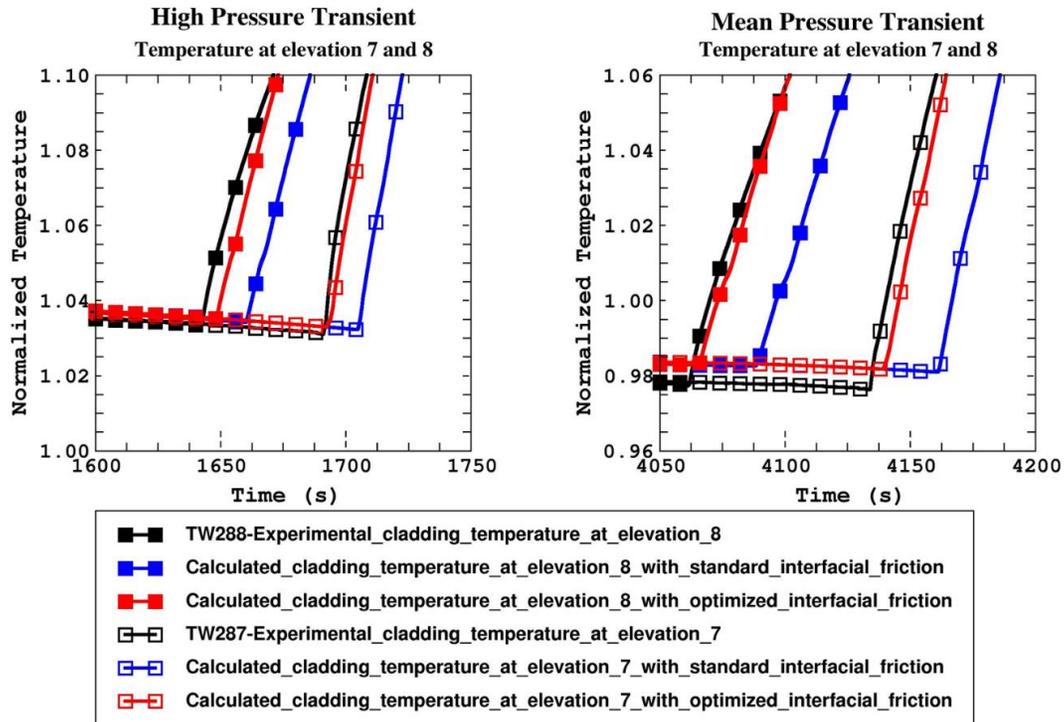


Fig. 5: Cladding temperature rising for the High (left) and Mean (right) Pressure transients

4.2. Dry Zone Behavior

Thanks to the symmetrical behavior of the core (the symmetrical is per 1/8), we only considered four assemblies (see Fig. 2): one High Power one, one Mean Power one and two Low Power (one full and one semi-crescent).

Comparisons between CATHARE calculations and experimental evolution for the cladding temperature of the High, Mean and Low (semi-crescent) power assemblies at elevation 7 are shown in Fig. 6 and Fig. 7. The cladding temperature for the High and Low (semi-crescent) power assemblies at elevation 8 are compared between CATHARE calculations and the experimental evolutions in Fig. 9. Comparisons show that the experimental cladding temperature are well predicted by the CATHARE code.

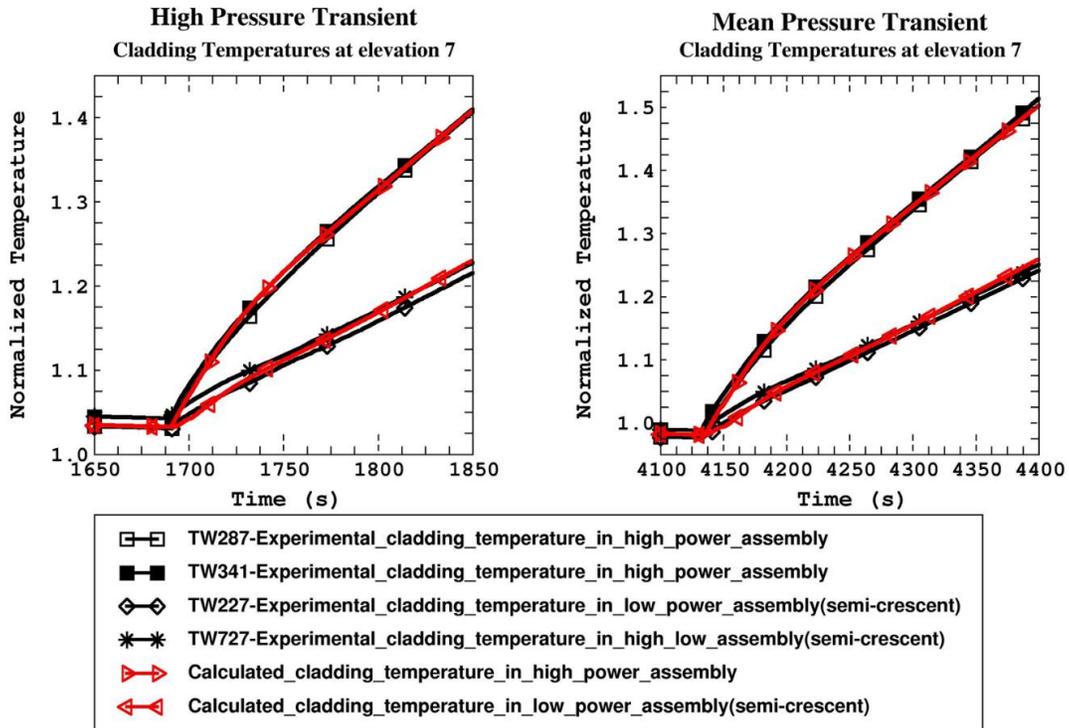


Fig. 6: Cladding temperatures at elevation 7 for the High (left) and Mean (right) Pressure transients

As presented in part 3.1, the vapor temperature is not homogeneous in the hot assembly, this imply that it is not possible to make a correct validation on the vapor temperature in the hot assembly. But, in the Mean Power assembly, thanks to symmetrical considerations, we manage to have the vapor evolutions at the four corner of the assembly. The experimental vapor temperature in the Mean Power assembly is quite homogeneous (see Fig. 7) and so, a comparison with CATHARE results is made (Fig. 7). The vapor temperature is overestimate by the code although the cladding temperature is well predicted. This can be explain by the position of the fluid temperature thermocouples, indeed, the fluid thermocouple are localized on non-heated rod, and the fluid can be a little cooler next to this non-heated rod. So, the experimental fluid temperature should be a little lower than the mean vapor temperature in the assembly given by CATHARE calculations.

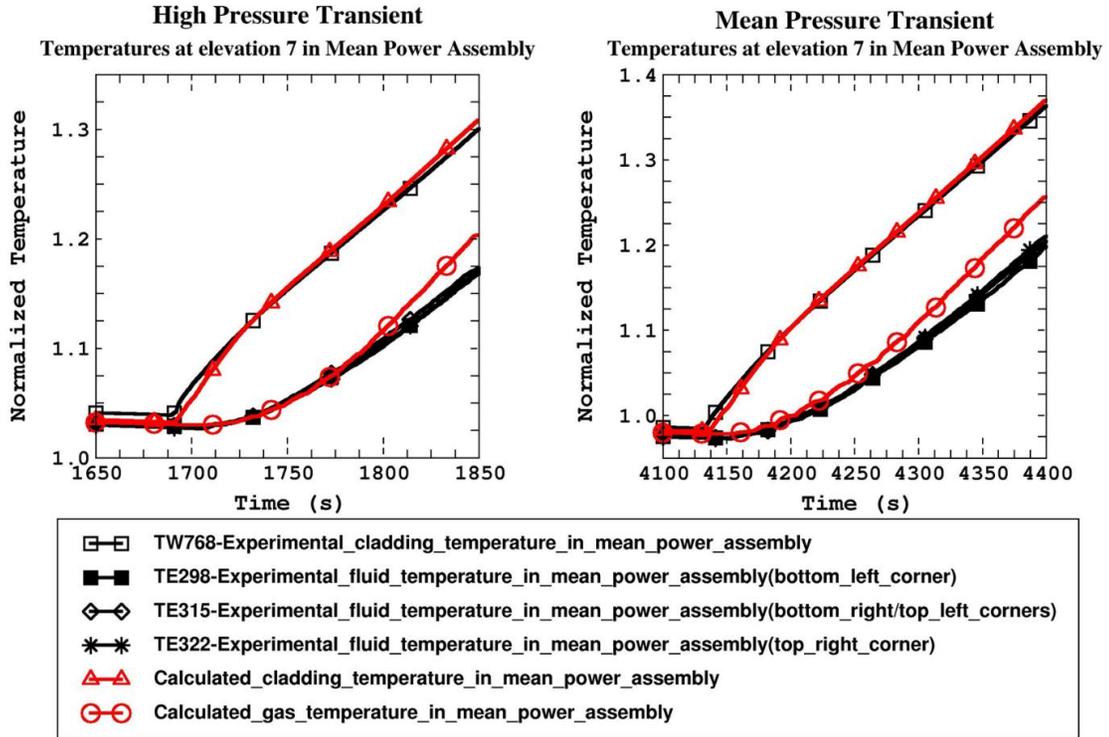


Fig. 7: Temperatures in the Mean Power Assembly at elevation 7 for the High (left) and Mean (right) Pressure transients

Moreover, “Chimney” effect is illustrate by the axial vapor mass flux profiles, plotted in Fig. 8. On this Figure, the axial mass flux is homogeneous at the swell level (about 2.5m for the High Pressure phase and 1.9m for the Mean Pressure phase) and differences which appears in the dry zone are due to the cross-flow. These cross-flow are important and the mass flux in the High power assembly reach twice the Low Power assembly mass flux.

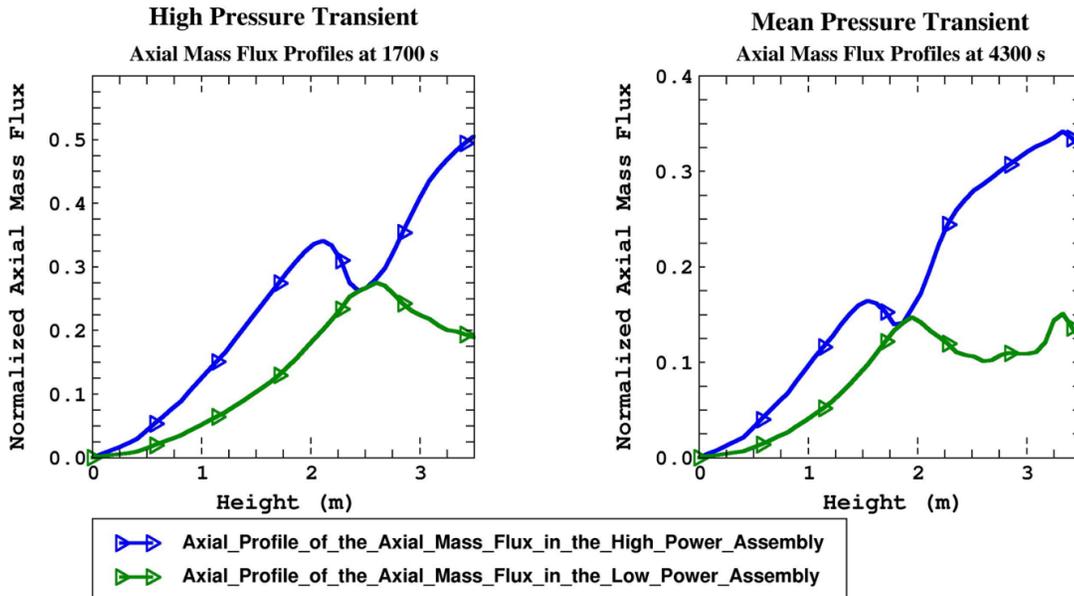


Fig. 8: Axial Mass Flux profiles at 1700s for the High (left) and at 4300s for Mean (right) Pressure transients

To illustrate the impact of “Chimney” effect on the cladding temperature of the hot assembly, a sensibility study has been made. In the radial directions, singular pressure drops have been increased in order to have penalized cross-flow and to reduce “Chimney” effect. The result is shown on Fig. 9; with penalized cross-flow, CATHARE overestimate the cladding temperature in the hot assembly and underestimate in the cold assembly. These results show that cross-flow in the dry zone must be taken into account to correctly predict the cladding temperatures.

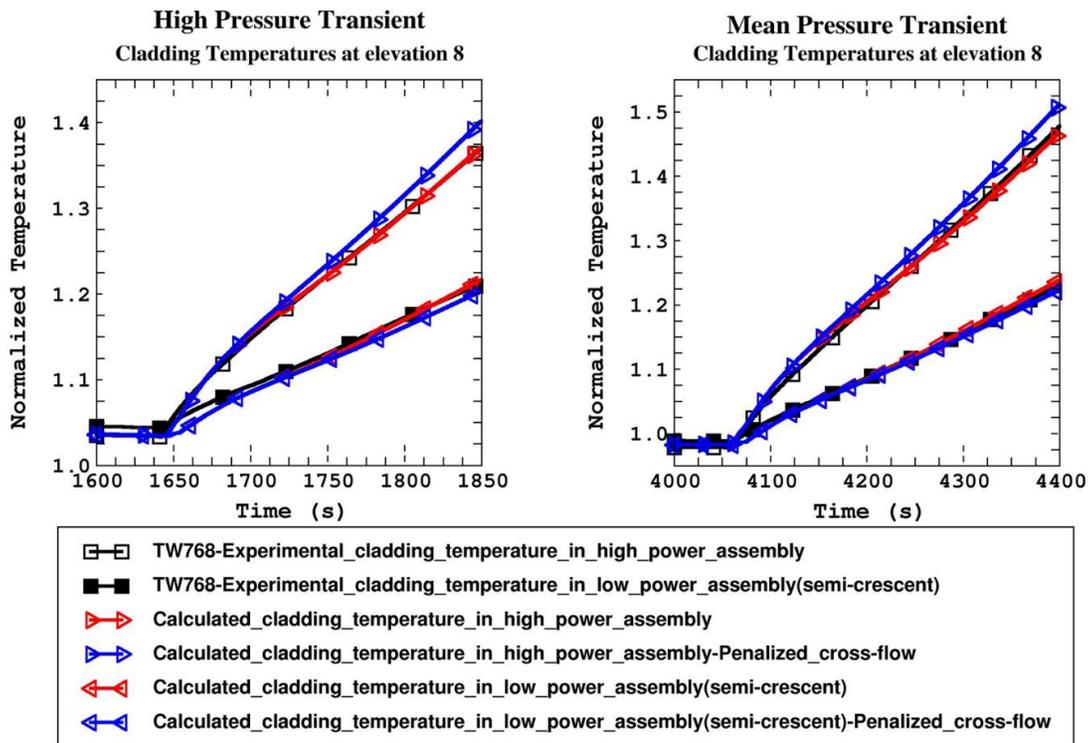


Fig. 9: Cladding temperatures at elevation 8 for the High (left) and Mean (right) Pressure transients

Others comparisons have been made against other experimental temperatures (for example, on the cladding temperature at elevation 6 or the vapor temperature at elevation 8). All give a good behavior of the CATHARE code against the experimental data.

4.3. Main Points of the Comparisons

From the presented comparisons, the main points are:

- The swell level is correctly predicted, and it is radially homogeneous in both CATHARE and the experiment. This shows that the interfacial friction model presented in part 2 is correct.
- Wall cladding temperature and vapor temperature are well predicted which shows that the wall to fluid coefficient in case of dry wall presented in part 2 is correct.
- “Chimney” effect (with cross-flows from the cold assemblies to the hot one) is present in the dry zone and must be taken into account to correctly predict the temperature in the hot assembly. Thus, the use of a 3-D Model of the core is necessary to correctly predict these situations

CATHARE 3-D Module has been validated against these two core uncover transient which are representative of thermal-hydraulic conditions occurring in case of IB-LOCA transient.

5. CONCLUSION

After presenting CATHARE 3-D Module and LSTF test 3; comparisons between CATHARE calculations and the experiment have been made on the two core uncover phases. Results shows that the 3-D Module of CATHARE is able to predict the core behavior during core uncover phase of IB-LOCA. And no shortcoming is associated to the use in the 3-D module of closure relations extrapolated from a 1D model. Moreover, as 3-D phenomena are present, the use of a 3-D module, instead of 1-D Module, is the right way to correctly predict the core behavior during IB-LOCA.

CATHARE simulations at sub-channel scale of ROSA2 test 3 core uncovering phases have also been made [15] and they show that that CATHARE is able to reproduce the right tendencies at sub-channel scale.

As shown in this article, singular pressure drops in the radial direction have an impact on the calculation results and there is an important uncertainty on the taken coefficient. The experimental program METERO [16], which will be made at CEA, will provide more information on transversal head loss in rod bundle geometry. METERO test section is composed by two half PWR assemblies and has the objective to enhance the validation of the models involved in 3D simulations of the core behavior during PWR LOCA.

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